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PRECISE MEASUREMENT OF FREE MOLECULE FLOW

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The attached paper lists most of the design philosophy evolved in the construction of the device. At this writing no decision has yet been reached on a source for the bellows but all other material is either on hand or on order. Fabrication is beginning with testing expected to commence in late June if the bellows can be secured in time.

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A VERY LOW FLOW RATE GAS

FLOW METER

by

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A B S T R A C T

Design philosophy and details for construction of a gas flow meter which will measure flow rates of 10^{-4} to 10^{-6} gm/sec. are presented.

A Very Low Flow Rate Gas Flow Meter

I. Introduction

With the advent of the space age, it has become necessary to investigate and to measure very low gas flow rate. The study of these flow rates arises in establishing leak rates and in the design and development of very low thrust nozzles which are used in control. For a thorough investigation to be made, it is necessary to have some method of measuring flow rates of 10^{-4} to 10^{-6} grams/sec.

Preferably the flow meter should operate at atmospheric pressure, because the properties of gases at this pressure are more readily determined. For accurate results a maximum error of 1% can be tolerated. A thorough survey of literature and catalogues was made to find existing flow meters which met these requirements.

A flow meter employing a very thin orifice will measure flow rates on the order of 10^{-2}gm./sec. with an error of 1 to 2%.[1] Modifications of this type meter to meet the desired specifications are difficult, because the pressure gradient across the orifice is not significant enough to measure accurately. To modify an orifice flow meter would require either reducing the volume flow rate of decreasing the density of the gas. Both methods of modification decrease the pressure gradient significantly.

The next flow meter considered was a type which employes rotating blades mounted in the flow stream (turbine type). This type of meter measures flow rates on the order of

10^{-2}gm./sec. and larger with a resolution of 1%.[1] To employ this type of meter to this operation would require the force exerted by the flow to be large enough to overcome the friction of the spindle and also turn the blades at a speed which would give accurate readings. The most applicable flow meter of this type would barely rotate in a flow rate of 10^{-6}gm./sec., and this would introduce appreciable errors in reading.

Another meter considered employs reciprocating bellows which are filled and emptied alternately, and the rate at which they operate determines the rate at which the mass enters the meter.[2] This type of meter is used to measure large flow rates, but it is of simple construction and was given much consideration. Application of this type meter in this problem involved using much smaller bellows and much more sensitive release valves. The use of smaller bellows would increase the reciprocating rate of the system, which should give better resolution by increasing the counts per unit time. A system of valves is employed to allow the mass of gas to escape the bellows when a given pressure is attained. This valve system also switches the inflow of gas to the other bellows which fills while the first one is emptying. After examining the valve system, it was decided that to apply this complex system to a very small pressure differential would require redesigning the entire valve system; this was too complex to consider with available resources.

The last flow meter investigated employes a falling piston which displaces a given volume of gas. To displace a volume of gas at a rate which would give a mass flow rate of 10^{-6}gm./sec. would require the piston to move at a very slow speed; at this speed all significant resolution is lost. From a survey of catalogues and literature it was concluded that no existing mass flow meter met the specifications.

II. Description of Operation

A new flow meter has been designed which will measure flow rates on the order of 10^{-4} to 10^{-6}gm./sec. The gas flow rate is established by a mechanical leak valve which allows the gas to leak from a constant pressure source into an evacuated system. If the flow is choked and the pressure is constant, the flow rate will remain constant. The volume of gas expelled is replaced by a piston which acts as a variable volume element. The piston is driven by a micrometer screw. The volume element is varied so that the pressure remains constant as determined by a differential pressure gauge. This pressure gauge runs a servo mechanism which drives the micrometer screw. The constant pressure, at which the flow meter operates, is determined by the pressure maintained in a reference tank attached to the differential pressure gauge. This pressure is read on a mechanical manometer open to the atmosphere. By adjusting the pressure and the valve, a wide range of flow rates can be obtained.

III. Design Analysis

A. Variable Volume Element

First consideration was given to the variable volume element, because other factors in the design depend on the type of element used. The constant pressure chamber will not be subjected to high temperatures or large pressure gradients across the walls; therefore, a glass tube is employed. The diameter of the glass tube is largely dependent on the resolution desired and the method used to obtain it. The headscrew has 28 threads and will travel .0357 inches per revolution. It was first planned to mount an indicator to the piston rod which would read the length traveled for a given time. This method would measure $\pm$ .05 inches and would be read on a scale by the operator. For cylinder diameters of 1/2 inch and larger the resolution obtained would not meet that specified.

It was decided, therefore, to mount a mechanical revolution counter to the drive shaft of the motor, which is geared at a 30:1 ratio to the leadscrew. Turning at 1300 r.p.m., the maximum number of readable digits will be 130 per minute or approximately two digits per second. Knowing that the landscrew travels .0357 inches per revolution, each digit will represent .0119 inches of travel by the piston. For a maximum mass flow rate of 10^{-4} grams/sec. at s.t.p., the volume displaced per second must be 2.89×10^{-6} 6ft^3/sec. for air. Assuming that an operating time of three minutes will allow enough time for the system to stabilize and give acceptable readings, the total volume displaced is 5.2×10^{-4}ft^3. Cylinder diameters ranging from 1/2 inch to 3 inches were considered. Noting that the variable volume element is composed of a constant area cylinder containing an adjustable piston, and the measurements are based on the piston travel; it is easily seen that the best resolution will be obtained by using a small diameter cylinder. The 1/2 inch diameter cylinder was picked assuming that the problem of sealing it to the piston could be solved. By employing the 1/2 inch diameter cylinder, the necessary travel length for a three minute run will be 4½ inches. This will require the drive shaft of the motor to turn at a maximum speed of 1300 r.p.m. The cylinder is a 1/2 inch I.D., precision bore, pyrex glass tube with tolerances of $\pm$ .0002 in. The piston size and material will be later determined by considering the sealing problem.

B. Fill and Exhaust Valves

The cylinder must be filled after each run by retracting the piston and passing gas through a fill valve. Also a leak valve must be provided to allow the gas to escape during operation, and the pressure gauge must be connected to the cylinder. To solve this problem a connection with three outlets was placed on the end of the glass tube. One outlet is connected to the pressure gauge, and Hoke valves are attached to the remaining two outlets. The fill valve will remain closed during the operating time.

C. Sealing Problem.

This problem mainly consists of designing a device which will provide a near perfect seal between the piston and the cylinder wall. It is very important that no gas be allowed to leak from the cylinder because any small leak would reduce the pressure in the chamber and thus indicate a larger volume change by the piston which is maintaining constant pressure. If the cylinder is operated below atmospheric pressures, the reverse is true. The order of magnitude of the flow rate being measured is small enough that a small leak would appreciably decrease the desired resolution.

The mecury seal was investigated first because it provides a perfect seal in most cases. To use this seal mercury is placed between two disks which are then tightened together by a screw adjustment. The mercury expands to seal the area. This type of seal would be applicable to this operation provided the chamber was always operated at atmospheric pressure. In previous applications of this seal, a leak developed when a pressure gradient was placed across the seal. Since it is desired to operate the flow meter at various chamber pressures, consideration of a mercury seal was discarded.

The O-ring type seal is very effective in sealing containers of liquids, and it also allows wide ranges of linear motion as, in this case, the piston travel length of 4½ inches. It seemed feasible to employ two O-rings with a sealing grease pack between them. If the chamber pressure is not lowered enough to blow the grease by the O-rings, this type of seal could be used. The main problem was the deposits of grease left on the cylinder wall after each run. Grease deposits in the chamber trap some gas by absorption and can also reduce the cross sectional area.

A new rolling bellows seal was investigated, but the manufacturer stated that the diameter of the seal needed to be three inches to provide an extension of 4.6 inches. The last type of seal considered and the type used in a bellows seal composed of many convolutions which allow extension and contraction. This type of seal is attached to the glass tube and to the piston. This will allow no gas to escape to the atmosphere, but appreciable gas may pass by the piston unless the extended bellows completely fills the area of the cylinder. By investigating existing bellows seals, it was found that the walls were too thick and the diameter decreased upon extension. This problem was assigned to a group of graduate students and a unique design was developed which will maintain a constant cross sectional area upon extension. Also several manufacturers of bellows seals were given the specifications with the hopes that they might be able to meet the requirements. At this time no seal has been produced and tested.

To estimate the motor size required, an existing bellows of 1/2 in. diameter was used. A force of seven pounds would be required to extend this bellows 4½ inches. Using this data and a safety factor of three to overcome friction losses and to drive the mechanical counter, the motor size was determined to be 1/50 H.P.

D. Pressure Gauge

The differential pressure gauge employed is model 306-2 manufactured by the Decker Corporation. This instrument provides a means for investigation of gas pressure in the low differential region. "The basic pressure meter consists of a capacitive transducer with associated electronics and calibrated barometric capsule. This instrument is designed to convert small changes in capacitance caused by small changes in pressure into large analogous output voltages."[3] When the input to the sensor having the greatest pressure is on the right, the meter will produce a positive voltage. A negative voltage is produced when the greatest pressure is on the left. The output voltage is $\pm$ 10 volts D.C. for all standard pressure ranges. The output impedance is 200 ohms and the output current is 2.5 milli-amps. This output current is to drive the servo-motor which will maintain constant pressure in the chamber. A reference tank is connected to the right side of the sensor which will produce a positive voltage and thus increase the speed of the motor when the chamber pressure falls below the pressure in the reference tank. If the piston overshoots before the system stabilizes, the chamber pressure will be greater than the pressure in the reference tank and the pressure meter will produce a negative voltage which will reverse the motor. A mechanical manometer is connected to the reference tank to determine the tank pressure. The tank pressure will be the stagnation pressure in the chamber after the system has become stable.

E. D.C. Amplifier and Power Supply

The 2.5 milli-amp output current from the pressure gauge will be used to control the servo-motor by controlling the armature current. The output current must be amplified by a D.C. power amplifier. The problem was solved by designing a D.C. amplifier and a power supply to drive the amplifier. (See Fig.2). The amplifier will produce 160 milli-amps at 115 volts D.C.

F. Servo Motor

The requirements placed on the motor are the following: 1/50 H.P., macimum speed of 1300 r.p.m., reversible and variable speed, and will develop approcimately 10 in. oz. of torque at 1300 r.p.m. These requirements were based on the force needed to extend the bellows and drive the speed reducer and counter. The model N S H -12 D.C. motor, manufactured by the Bodine Company, meets these requirements and will be empolyed in this operation.

G. Speed Reducer

A major problem developed in reducing the speed of the drive shaft from the motor to the drive of the piston. A reduction of 30:1 is desired. To obtain resolution of 1% every possible error must be minimized, and the speed reducer and coupling devices are appreciable sources of error. The error arises from the back lash introduced into the system. Backlash in gears is play between mating teeth and occurs when gears are engaged. The smaller the desired backlash, the more accurate the matching of gears must be. To design and build this speed reducer would require percision instruments and expert craftsmanship; therefore, an investigation was made to find an existing apparatus which would give a speed reduction of 30:1 and have minimum backlash. The P.I.C. Design Corporation produces a precision servo gear box which has a backlash of 30 minutes. The backlash is measured at the output with input locked. The coupling problem was solved by employing a bellows coupling with no backlash. The coupling must connect shafts of two different diameters; this type of coupling device can also be ordered from P.I.C. Design Corporation.

H. Leadscrew Assembly

The method of driving the piston is to be a micrometer screw which will be used to measure the distance traveled by the piston. The leadscrew assembly will consist of a threaded block to which the piston rod will be attached. As the lead screw turns, the block advances and thus the piston moves down the cylinder. The length of travel of the block is to be five inches. Micro-switches are mounted at both ends of the lead screw assembly and will cut off the motor when the block reaches the end of the screw. These switches are used aa a safety factor to keep the motor from stripping the gears if the operator fails to cut off the motor manually.

IV. Conclusion

By knowing the pressure and temperature in the chamber, the density of the gas may be determined. Measuring the total valume change for a given time to the nearest .002 sq.in. and the density, the mass flow rate may be determined with a resolution of 1% This is now being favricated for testing later this year.

R e f e r e r e n c e s

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2. A. Linford, Flow Measurement and Meters, E and F.N Spon Ltd.
3. Decker Corporation. Model 306-2 Operation Manual.